

Death of Stellar Baryonic Dark Matter

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Abstract. The nature of the dark matter in the haloes of galaxies is one of the outstanding questions in astrophysics. All stellar candidates, until recently thought to be likely baryonic contributions to the Halo of our Galaxy, are shown to be ruled out. Faint stars and brown dwarfs are found to constitute only a few percent of the mass of the Galaxy. Stellar remnants, including white dwarfs and neutron stars, are shown to be very constrained as well. High energy gamma-rays observed in HEGRA data place the strongest constraints, $\Omega_{WD} < 3 \times 10^{-3} h^{-1}$, where h is the Hubble constant in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Hence one is left with several unanswered questions: 1) What are MACHOs seen in microlensing surveys? 2) What is the dark matter in our Galaxy? Indeed a nonbaryonic component in the Halo seems to be required.

1 Introduction

The nature of the dark matter in the haloes of galaxies is an outstanding problem in astrophysics. Over the last several decades there has been great debate about whether this matter is baryonic or must be exotic. Many astronomers believed that a stellar or substellar solution to this problem might be the most simple and therefore most plausible explanation. However, in the last few years, these candidates have been ruled out as significant components of the Galactic Halo. I will discuss limits on these stellar candidates, and argue for my personal conviction that: *Most of the dark matter in the Galactic Halo must be nonbaryonic.*

Until recently, stellar candidates for the dark matter, including faint stars, brown dwarfs, white dwarfs, and neutron stars, were extremely popular. However, recent analysis of various data sets has shown that faint stars and brown dwarfs probably constitute no more than a few percent of the mass of our Galaxy [1,2,3,4,5,6]. Specifically, using Hubble Space Telescope and parallax data, we showed that faint stars and brown dwarfs contribute no more than 1% of the mass density of the Galaxy. Microlensing experiments (the MACHO [8], [9] and EROS [10]) experiments), which were designed to look for Massive Compact Halo Objects (MACHOs), also failed to find these light stellar objects and ruled out substellar dark matter candidates in the $(10^{-7} - 10^{-2}) M_{\odot}$ mass range.

Recently white dwarfs have received attention as possible dark matter candidates. Interest in white dwarfs has been motivated by microlensing events

interpreted as being in the Halo, with a best fit mass of $\sim 0.5M_{\odot}$. However, I will show that stellar remnants including white dwarfs and neutron stars are extremely problematic as dark matter candidates. A combination of excessive infrared radiation, mass budget issues and chemical abundances constrains the abundance of stellar remnants in the Halo quite severely, as shown below. Hence, white dwarfs, brown dwarfs, faint stars, and neutron stars are either ruled out or extremely problematic as dark matter candidates. Thus the puzzle remains, What are the 14 MACHO events that have been interpreted as being in the Halo of the Galaxy? Are some of them actually located elsewhere, such as in the LMC itself? These questions are currently unanswered. As regards the dark matter in the Halo of our Galaxy, one is driven to nonbaryonic constituents as the bulk of the matter. Possibilities include supersymmetric particles, axions, primordial black holes, or other exotic candidates.

In this talk I will focus on the arguments against stellar remnants as candidates for a substantial fraction of the dark matter, as white dwarfs in particular have been the focus of attention as potential explanations of microlensing data. For a discussion of limits on faint stars and brown dwarfs, see earlier conference proceedings by Freese, Fields, and Graff ([6] and [7]).

2 White Dwarfs

Stellar remnants (white dwarfs and neutron stars) face a number of problems and issues as dark matter candidates: 1) infrared radiation; 2) IMF (initial mass function); 3) baryonic mass budget; 4) element abundances.

We find that none of the expected signatures in the above list of a significant white dwarf component in the Galactic Halo are seen to exist.

2.1 Constraints from multi-TeV γ -rays seen by HEGRA

The mere existence of multi-TeV γ -rays seen in the HEGRA experiment places a powerful constraint on the allowed abundance of white dwarfs. This arises because the progenitors of the white dwarfs would produce infrared radiation that would prevent the γ -rays from getting here. The γ -rays and infrared photons would interact via $\gamma\gamma \rightarrow e^+e^-$.

Multi-TeV γ -rays from the blazar Mkn 501 at a redshift $z=0.034$ are seen in the HEGRA detector. The cross section for (1-10)TeV γ -rays peaks at infrared photon energies of (0.03-3)eV. Photons in this energy range would be produced in abundance by the progenitor stars to white dwarfs and neutron stars. By requiring that the optical depth due to $\gamma\gamma \rightarrow e^+e^-$ be less than one for a source at $z = 0.034$ we limit the cosmological density of stellar remnants [14] to $\Omega_{\text{WD}} \leq (1-3) \times 10^{-3}h^{-1}$. This constraint is quite robust and model independent, as it applies to a variety of models for stellar physics, star formation rate and redshift, mass function, and clustering.

2.2 Mass Budget Issues

Contribution of Machos to the Mass Density of the Universe: (based on work by Fields, Freese, and Graff [15]) There is a potential problem in that too many baryons are tied up in Machos and their progenitors (Fields, Freese, and Graff). We begin by estimating the contribution of Machos to the mass density of the universe. Microlensing results [8] predict that the total mass of Machos in the Galactic Halo out to 50 kpc is $M_{\text{Macho}} = (1.3 - 3.2) \times 10^{11} M_{\odot}$. Now one can obtain a “Macho-to-light” ratio for the Halo by dividing by the luminosity of the Milky Way (in the B-band), $L_{MW} \sim (1.3 - 2.5) \times 10^{10} L_{\odot}$, to obtain $(M/L)_{\text{Macho}} = (5.2 - 25) M_{\odot}/L_{\odot}$. From the ESO Slice Project Redshift survey [16], the luminosity density of the Universe in the B band is $\mathcal{L}_B = 1.9 \times 10^8 h L_{\odot} \text{ Mpc}^{-3}$. If we assume that the M/L which we defined for the Milky Way is typical of the Universe as a whole, then the universal mass density of Machos is

$$\Omega_{\text{Macho}} \equiv \rho_{\text{Macho}}/\rho_c = (0.0036 - 0.017) h^{-1} \quad (1)$$

where the critical density $\rho_c \equiv 3H_0^2/8\pi G = 2.71 \times 10^{11} h^2 M_{\odot} \text{ Mpc}^{-3}$.

We will now proceed to compare our Ω_{Macho} derived in Eq. 1 with the baryonic density in the universe, Ω_B , as determined by primordial nucleosynthesis. To conservatively allow for the full range of possibilities, we will adopt $\Omega_B = (0.005 - 0.022) h^{-2}$. Thus, if the Galactic halo Macho interpretation of the microlensing results is correct, Machos make up an important fraction of the baryonic matter of the Universe. Specifically, the central values give

$$\Omega_{\text{Macho}}/\Omega_B \sim 0.7. \quad (2)$$

However, the lower limit on this fraction is considerably less restrictive,

$$\frac{\Omega_{\text{Macho}}}{\Omega_B} \geq \frac{1}{6} h \geq \frac{1}{12}. \quad (3)$$

Mass Budget constraints from Machos as Stellar Remnants: White Dwarfs or Neutron Stars In general, white dwarfs, neutron stars, or black holes all came from significantly heavier progenitors. Hence, the excess mass left over from the progenitors must be added to the calculation of Ω_{Macho} ; the excess mass then leads to stronger constraints. Typically we find the contribution of Macho progenitors to the mass density of the universe to be $\Omega_{\text{prog}} = 4\Omega_{\text{Macho}} = (0.016 - 0.08)h^{-1}$. The central values of all the numbers now imply $\Omega_{\text{prog}} \sim 3\Omega_B$, which is obviously unacceptable. One is driven to the lowest values of Ω_{Macho} and highest value of Ω_B to avoid this problem.

2.3 On Carbon and Nitrogen

The overproduction of carbon and/or nitrogen produced by white dwarf progenitors is one of the greatest difficulties faced by a white dwarf dark matter

scenario, as first noted by Gibson and Mould [17]. Stellar carbon yields for zero metallicity stars are quite uncertain. Still, according to the yields by [21], a star of mass $2.5M_{\odot}$ will produce about twice the solar enrichment of carbon. However, stars in our galactic halo have carbon abundance in the range $10^{-4} - 10^{-2}$ solar. Hence the ejecta of a large population of white dwarfs would have to be removed from the galaxy via a galactic wind.

However, carbon abundances in intermediate redshift Ly α forest lines have recently been measured to be quite low, at the $\sim 10^{-2}$ solar level [18], for Ly α systems at $z \sim 3$ with column densities $N \geq 3 \times 10^{15} \text{ cm}^{-2}$ (for lower column densities, the mean C/H drops to $\sim 10^{-3.5}$ solar [19]).

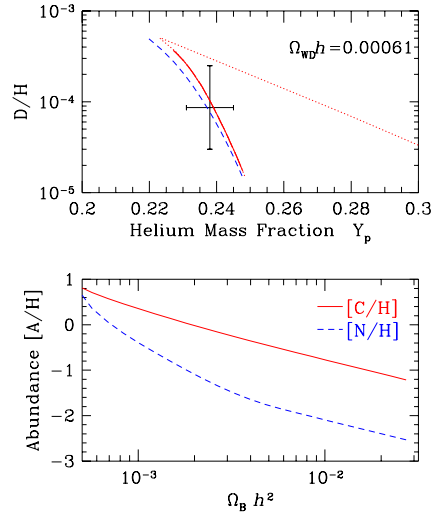


Fig. 1. (taken from Fields, Freese, and Graff 1999): **(a)** The D/H abundances and helium mass fraction Y for models with $\Omega_{WD}h = 6.1 \times 10^{-4}$, $h = 0.7$, and IMF peaked at $2M_{\odot}$. The short-dashed curve shows the initial abundances and the error bars the range of D and He measurements. The other three curves show the changes in primordial D and He as a result of white dwarf production. The solid one is for the full chemical evolution model, the dotted one for instantaneous recycling, and the long-dashed one for the burst model. This is the absolute minimum Ω_{WD} compatible with cosmic extrapolation of white dwarf Machos if Machos are contained only in spiral galaxies with luminosities similar to the Milky Way. **(b)** CNO abundances produced in the same model as **a**, here plotted as a function of Ω_B . The CN abundances are presented relative to solar via the usual notation of the form $[C/H] = \log_{10} \frac{C/H}{(C/H)_{\odot}}$. The C and N production in particular are greater than 1/10 solar.

In order to maintain carbon abundances as low as 10^{-2} solar, only about 10^{-2} of all baryons can have passed through the intermediate mass stars that were the predecessors of Machos [15]. Such a fraction can barely be

accommodated for the remnant density predicted from our extrapolation of the Macho group results, and would be in conflict with Ω_{prog} in the case of a single burst of star formation. Note that stars heavier than $4M_{\odot}$ may replace the carbon overproduction problem with nitrogen overproduction [21,22].

Using the yields described above, we calculated the C and N that would result from the stellar processing for a variety of initial mass functions for the white dwarf progenitors. We used a chemical evolution model based on a code described in Fields & Olive [23] to obtain our numerical results. Our results are presented in the figure.

In the figure, we make the parameter choices that are in agreement with D and He^4 measurements (see the discussion below) and are the least restrictive when comparing with the $\text{Ly}\alpha$ measurements. We take an initial mass function (IMF) sharply peaked at $2M_{\odot}$, so that there are very few progenitor stars heavier than $3M_{\odot}$ (this IMF is required by D and He^4 measurements). In addition (see the figures in Fields, Freese, and Graff [20]) we have considered a variety of other parameter choices. By comparing with the observations, we obtain the limit, $\Omega_{\text{WD}}h \leq 2 \times 10^{-4}$. As a caveat, note that it is possible that carbon never leaves the (zero metallicity) white dwarf progenitors, so that carbon overproduction is not a problem [24].

2.4 Deuterium and Helium

Because of the uncertainty in the C and N yields from low-metallicity stars, we have also calculated the D and He^4 abundances that would be produced by white dwarf progenitors. These are far less uncertain as they are produced farther out from the center of the star and do not have to be dredged up from the core. Panel a) in the figure displays our results. Also shown are the initial values from big bang nucleosynthesis and the (very generous) range of primordial values of D and He^4 from observations. From D and He alone, we can see that the white dwarf progenitor IMF must be peaked at low masses, $\sim 2M_{\odot}$. We obtain $\Omega_{\text{WD}} \leq 0.003$.

3 Conclusions

A Zero Macho Halo? The possibility exists that the 14 microlensing events that have been interpreted as being in the Halo of the Galaxy are in fact due to some other lensing population. One of the most difficult aspects of microlensing is the degeneracy of the interpretation of the data, so that it is currently impossible to determine whether the lenses lie in the Galactic Halo, or in the Disk of the Milky Way, or in the LMC. In particular, it is possible that the LMC is thicker than previously thought so that the observed events are due to self-lensing of the LMC. All these possibilities are being investigated. More data are required in order to identify where the lenses are.

Microlensing experiments have ruled out baryonic dark matter objects in the mass range $10^{-7}M_{\odot}$ all the way up to $10^{-2}M_{\odot}$. In this talk I discussed the heavier possibilities in the range $10^{-2}M_{\odot}$ to a few M_{\odot} . Brown dwarfs and faint stars are ruled out as significant dark matter components; they contribute no more than 1% of the Halo mass density. Stellar remnants are not able to explain the dark matter of the Galaxy either; none of the expected signatures of stellar remnants, i.e., infrared radiation, large baryonic mass budget, and C,N, and He^4 abundances, are found observationally.

Hence, in conclusion,

- 1) Nonbaryonic dark matter in our Galaxy seems to be required, and
- 2) The nature of the Machos seen in microlensing experiments and interpreted as the dark matter in the Halo of our Galaxy remains a mystery. Are we driven to primordial black holes [25] [26], nonbaryonic Machos (Machismos?), mirror matter Machos ([27]) or perhaps a no-Macho Halo?

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